A risk-based approach to improve monitoring and performance of remote waste stabilisation ponds

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ABSTRACT

A cost-effective risk-based system was developed for assessing the performance and potential environmental impact of a large number of geographically dispersed pond systems, where cost and logistical issues prevent direct monitoring. In the process, a range of risk functions were calculated for each site to take into account pond performance, receiving environment, influent quality, surrounding land use and system size. Pond performance was estimated using traditional design equations, including Monte Carlo analysis to account for uncertainty in boundary conditions. The calculation of combined risk functions for all systems enabled the quantitative ranking of systems, which can be used to prioritise limited sampling resources.

Key words | cost effective, monitoring, waste stabilisation ponds

INTRODUCTION

The Northern Territory (NT) occupies the central northern region of the Australian continent. The territory is the most sparsely populated area of Australia, with an average population density of 0.2 persons/km². Waste stabilisation ponds are used for wastewater treatment in 56 of the 72 remote Indigenous communities in the Northern Territory. The locations of these communities are shown in Figure 1. The communities range in size from less than 100 residents to almost 3,000 residents. The Northern Territory has two distinct climatic zones: monsoonal tropics in the north and desert in the south. For many communities access is dry weather only, with long stretches of unsealed roads and unsealed airstrips.

Residents of communities are often highly mobile and population numbers in communities can change rapidly. As a result, water usage patterns vary between similarly sized non-Indigenous communities, and historical sampling of raw wastewater volume and quality has been very limited. These factors all contribute to a dearth of understanding of wastewater treatment capacity requirements and treatment performance. To provide a basis for design, a set of Indigenous Community Engineering Guidelines (ICEGs) have been developed. These provide design benchmarks which stipulate the target wastewater flow and quality based on estimated population. The ICEGs also provide very simple pond design criteria, as follows:

- One facultative pond followed by three maturation ponds.
- Facultative pond depth 1.8m, maturation pond depth 1.5 m.
- Facultative pond loading 150–350 kg biological oxygen demand (BOD)/(ha·d), based on pond latitude.
- 10 days residence time in facultative pond, 20 days total residence time in maturation ponds.

Eleven of the pond systems in operation adhere to this standard pond configuration; 44 other sites employ the same general configuration but with only one or two maturation ponds. The only notable exception is Galiwinku, where an anaerobic pond is used in place of a primary facultative pond. Most wastewater pump stations include macerators, and no pre-screening of lagoon flow occurs. Pond geometries and pipework configurations are not covered by the ICEGs, and vary widely between sites.

However, the limited sampling conducted to date has identified that actual flowrates and loadings can vary widely from ICEG values. Raw wastewater BOD results were in many cases significantly lower than the ICEG value of 200 mg/L. It can be difficult to compare volume to the ICEG benchmark due to uncertainty about actual population levels; however, water consumption and
wastewater production vary broadly with geography and water availability. In the tropical north, wastewater production rate generally exceeds the ICEG benchmark, while in the water stressed southern areas wastewater production rate may be significantly lower than the ICEG benchmark.

To address the shortage of information about treatment requirements and pond performance, detailed monitoring of raw and treated wastewater quality and volume is required. However the options for monitoring pond performance are very limited in these circumstances. Many communities have a limited availability of skilled operators, and highly mobile populations can make it difficult to retain trained staff. The nearest accredited laboratories are located in Alice Springs and Darwin, which in some cases are more than 700 km distant from the community. Historically, these ponds systems have operated with little operational or regulatory scrutiny, and as a result little is known about the wastewater entering these pond systems or the performance of the ponds.

Recently there has been an improved focus on the environmental impact and health risks associated with these pond systems. However, the large number of systems, the extremely high costs and impracticalities of monitoring, and limited resources are all barriers to identifying poorly performing pond systems.

More detailed operating information is required for all pond systems, for the purposes of understanding and optimising behaviour, identifying upgrades, improving design, and assessing environmental impact from operation. However, for the reasons outlined above it is not currently feasible to initiate a monitoring program for all 56 pond systems.

**METHOD: SYSTEM EVALUATION PROCESS**

To work towards the aim of improved pond understanding, a risk-based approach has been developed to evaluate predicted pond performance and prioritise individual sites for further action. The approach consists of the following steps:

(A) Theoretical pond performance is modelled.
(B) Model results are evaluated and performance risk quantified.
(C) Pond performance risk is included in a broader risk assessment.
(D) Overall risk of pond system to environment is quantified and ranked.
(E) Key high risk sites are identified for further action.

**Pond performance evaluation**

The theoretical performance of each pond system was estimated using standard process design equations to model the removal of five constituents of wastewater; BOD, *Escherichia coli*, helminth eggs, ammonia (NH₃) and total Kjeldahl nitrogen (TKN). BOD loading and removal in anaerobic ponds were estimated using the anaerobic design equations suggested by Mara (2003). In order to take into account the impact of pond geometry on performance, removal of BOD and *E. coli* in facultative ponds was calculated using the one-dimensional dispersion model suggested by von Sperling (2005). Where baffles were present in a pond, the length-to-width ratio of the pond was corrected to represent the effect of the baffles on the pond geometry. The facultative BOD decay constant was developed from empirical data published by da Silva et al. (1993), while the *E. coli* decay constant was as suggested by von Sperling (2005). Fully empirical models were used for predicting the removal of NH₃ (Pano & Middlebrooks 1982; Silva et al. 1995), TKN (Reed 1985) and helminth eggs (Ayres et al. 1992) based on local temperature, residence time and (for NH₃ and TKN) wastewater pH. The performance of each pond in each series was evaluated sequentially to predict the overall pond system performance with respect to the removal of each parameter.

Model inputs were estimated based on the ICEGs, or calculated accurately where data were available. The impact of uncertainty in the model inputs was accounted for by including a variability factor in the model inputs and using a Monte Carlo analysis (see Figure 2). The input parameters for the models are listed in Table 1, along with the variability ranges used for the Monte Carlo analysis. In
each case the variability ranges were estimates based on likely or known variability at each site.

The models were established as Microsoft Excel spreadsheets for each site. 10,000 independent model runs were conducted for each pond, based on randomly generated uniform distributions of input boundary conditions (von Sperling 1996).

For further analysis, BOD and E. coli removals were adopted as key indicators of pond system performance. Nutrient removal was excluded from the analysis due to concerns about the accuracy of modelling results (see results below). A risk function (RF) between 1 and 5 was calculated for each site for BOD and E. coli, based on the following:

Table 1 | Model inputs, including range of variability used for Monte Carlo analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion number</td>
<td>Calculated from length-to-width ratio</td>
<td>±20%</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Based on published meteorology data for communitya</td>
<td>±2 mm/day</td>
</tr>
<tr>
<td>Influent BOD</td>
<td>200 mg/L</td>
<td>±40 mg/L</td>
</tr>
<tr>
<td>Influent E. coli</td>
<td>10⁶/100 mL</td>
<td>10⁶–10⁷/100 mL</td>
</tr>
<tr>
<td>Influent helminth eggs</td>
<td>100 eggs/L</td>
<td>100–1,000 eggs/L</td>
</tr>
<tr>
<td>Influent NH₃</td>
<td>28.5 mg/L</td>
<td>±11.5 mg/L</td>
</tr>
<tr>
<td>Influent TKN</td>
<td>51.5 mg/L</td>
<td>±21.5 mg/L</td>
</tr>
<tr>
<td>Population</td>
<td>Based on published community estimatesb</td>
<td>None</td>
</tr>
<tr>
<td>Sludge depth</td>
<td>12.75% of pond depth where sludge depth unknown</td>
<td>±12.75% of pond depth where sludge depth unknown</td>
</tr>
<tr>
<td></td>
<td>75% of average surveyed sludge depth where sludge depth known</td>
<td>±25% of surveyed sludge depth where sludge depth known</td>
</tr>
<tr>
<td>Wastewater pH</td>
<td>8.0</td>
<td>±2.0</td>
</tr>
<tr>
<td>Wastewater temperature</td>
<td>Based on mean dry season/winter air temperature at nearest station to communityb</td>
<td>±2°C</td>
</tr>
</tbody>
</table>


bCommunity population data based on unpublished Northern Territory Government data.
BOD: RF = 1 for removal ≥ 80%, RF = 5 for removal ≤ 20%, linear gradient in between.

E. coli: RF = 1 for removal ≥ 5 log, RF = 5 for removal ≤ 1 log, linear gradient in between.

A normalised geometric norm of the two risk functions was calculated to combine both parameters. The resulting treatment RF provided a net ranking of all 56 sites, based on predicted BOD and E. coli removal, and a quantitative indication of the predicted treatment performance of each on a scale between excellent predicted performance (low risk, RF = 1) and very poor predicted performance (high risk, RF = 5).

Inclusion of other risk functions

While the performance of each pond system is a key factor when determining the impact of the treated wastewater on the environment, a number of other attributes are also critical. These are:

1. Type of receiving environment/site conservation value.
2. The composition and constituents of the raw wastewater at the site.
3. Surrounding land use and potential for impact.
4. The scale of the system.

Separate risk functions were assigned for each of these attributes for each system, using standard facility evaluation guidelines employed by Power and Water Corporation.

Receiving environment

Risk functions for receiving environments were assigned using the criteria in Table 2.

Wastewater composition

As all pond systems service communities which are predominantly domestic in nature with little industry, all sites were assigned a risk function of 3 with respect to this attribute.

Table 2 | Receiving environment risk functions

<table>
<thead>
<tr>
<th>Conservation value</th>
<th>Receiving environment type</th>
<th>Saline</th>
<th>Brackish</th>
<th>Fresh/groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pristine</td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Minor disturbance</td>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Major disturbance</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Surrounding land use

The most critical surrounding land use was determined to be the proximity of the site to bores used for drinking water supply. A risk function was assigned for this attribute using the following criteria:

- RF = 5 for sites ≤ 500 m from bore.
- RF = 4 for sites > 500 m, ≤ 1 km from bore.
- RF = 3 for sites > 1 km, ≤ 1.5 km from bore.
- RF = 2 for sites > 1.5 km, ≤ 2 km from bore.
- RF = 1 for sites > 2 km from bore.

Size of the system

Approximate population size of each community was used as a surrogate for volumetric flow for the purposes of determining a size risk function. While wastewater production per capita varies widely between sites, population is a more consistent indicator of overall system loading. A risk function was assigned for this attribute using the following criteria:

- RF = 5 for populations > 1,500.
- RF = 4 for populations > 1,000, ≤ 1,500.
- RF = 3 for populations > 500, ≤ 1,000.
- RF = 2 for populations > 200, ≤ 500.
- RF = 1 for populations ≤ 200.

Combined risk function

A total combined risk function was calculated as the product of the five attribute risk functions. The resulting combined RF provided a means of ranking the 56 sites based on the overall risk to the environment resulting from the treatment, disposal and other circumstances of the systems.

RESULTS AND DISCUSSION

Pond results and ranking

The treatment performance model results for the 56 pond systems are shown in Figures 3–6. The figures show predicted removal across all ponds at each site. In each case the 50th percentile for the model results distribution is shown, with the 5th and 95th percentiles marked by error bars. In each figure the communities are ranked with respect to their mean predicted removal performance of the parameter.
It is evident from Figure 3 that predicted BOD removal varies widely between sites, in the range of 30% to greater than 80% total removal. Only a handful of pond systems at the upper end of the results could be considered to be satisfactorily sized for BOD removal. Similarly, in Figure 4 the range of *E. coli* performance varies widely between sites, with five sites exceeding a predicted *E. coli* removal of 5 log.

Almost all sites are satisfactory with respect to predicted helminth egg removal (Figure 5), with only 12 sites predicting helminth egg removals of less than log 4 across the pond system. Log 4 is considered an adequate minimum level of removal where influent concentrations are in the range of 100–1,000 eggs/L.

Predicted nitrogen removal is generally high across all sites, with the predicted NH$_3$ removal in the 50th percentile greater than 70% at the majority of sites, and greater than 95% at 12 sites (Figure 6). These results meet or exceed published expectations (e.g. 73 to 80%, Soares et al. 1996; up to 95%, Mara & Pearson 1998); however, the 95th percentile limit is below 20% removal for 23 sites, or over 40% of the total sites studied. The large skew in the distribution of the NH$_3$ results (and similarly the TKN results, not shown) appears to have been caused by the large range in input
pH values to the model. More accurate and representative pH data may produce more representative predictions for these parameters.

While overall there are general similarities in pond system performance with respect to each parameter, there are a number of exceptions where sites performed well with respect to some parameters but not others.

**Combined risk function**

There was considerable variation in the calculated combined RF between sites: from 12 at the lowest risk site to 611 at the highest risk site. The final system rankings are in many cases very different to the rankings shown in Figures 3–6. Highest risk sites are typically sites with a combination of circumstances including poor predicted treatment performance, larger populations, and river or marine receiving environments.

While this general result could be anticipated, the process provides a quantitative result which takes into account all the individual site-specific factors at each site. Being able to quantitatively discriminate between sites is essential when ranking such a large number of sites with such high variability in individual treatment and disposal conditions between sites.
As the definitions used to assign risk factors for each attribute were adopted from standard facility evaluation guidelines, alternative assessment attributes or RF weighting schemes were not investigated. Where existing assessment attributes are not available or are not appropriate, the choice of attributes and risk factors for other assessments require careful consideration. The weighting of each attribute should reflect how important that attribute is in the local context.

Preliminary validation

A preliminary validation of the process was undertaken for one of the 56 sites. The ponds at Galiwinku consist of a primary anaerobic pond followed by a baffled maturation pond. However, visual observations and limited monitoring data suggest that the primary pond typically operates as a facultative pond, most probably due to low strength wastewater inflow. As with other sites, the model was run for Galiwinku using the boundary data outlined in Table 1. For the purposes of modelling the site, the primary pond was assumed to be a facultative pond, and the secondary pond a maturation pond. The model results were compared with a sampling dataset which contained 2–3 data points per site, obtained across a number of months during the year.

Results from the modelling are compared with sampled data from the site in Figures 7 and 8. It is evident from both figures that the field data agree well with the results of the predictive modelling. However, it must be noted that very limited data were available for validation.

Further monitoring and validation

Based on the ranking, a small number of sites can be chosen for a detailed monitoring program. In the event that validation is the only objective and resources are plentiful, a range of pond types with varied locations and risk rankings should be chosen for monitoring. If monitoring data will also be used for other purposes, for example as design data for upgrades, then a focus on the highest risk sites would be prudent. In this study, the highest risk sites were selected for physical monitoring for the following reasons:

- The sites are in close proximity, reducing transport and logistical issues for sampling. A single aerial-based sampling run can be used to collect samples from all sites.
- As all the sites are communities with higher populations, more skilled personnel are available to undertake sampling.

Trial sampling and analysis of the pond inflow and outflow are planned in a small number of sites. By establishing the quantity and quality of effluent entering and exiting each pond system, the following can be established:

- The accuracy and variability of the boundary conditions used in modelling the predicted performance of the pond systems. Where these vary significantly from initial assumptions, the model may be re-run using new boundary conditions.
- The accuracy of the predicted treatment model results. This can be used to infer the accuracy of the approach as used at other sites which are not being monitored.
- Appropriate design parameters for pond upgrades or new installations.

Ultimately, if the validation process shows this to be a robust and accurate method of assessing performance, this approach may be used to limit the long term monitoring requirements to a number of sites, significantly reducing monitoring costs.

Limitations of the approach

As with any modelling-based analysis, the accuracy of the assumptions used for the modelling is a key source of potential error. In the absence of detailed inflow data, the assumptions used for inflow volume and quality are known to be subject to a high degree of uncertainty.
Similarly, population estimates can vary widely for individual communities. Due to the difficulty of quantifying population variability, variability estimates were not included in the Monte Carlo analysis. A detailed investigation of population statistics could be used to improve the accuracy of the approach. Finally, the theoretical models used as the basis of the investigation are partly or wholly empirical in nature, and are not definitive descriptors of pond operation (Ellis & Rodrigues 1993).

CONCLUSION

This paper has described the development of a risk-based approach for quantitatively ranking pond performance for a large number of geographically-dispersed pond systems. The approach provides the following:

- A cost-effective initial benchmark of pond performance and risk where previously no benchmark existed.
- The possibility of undertaking a feasible targeted sampling program on a small subset of pond systems to validate the modelling approach and infer the performance of all 56 systems. Due to logistical and geographical issues, it may not be feasible to sample more than a small subset of ponds on an ongoing basis.

The following factors should be considered when undertaking a similar approach:

- As with all modelling approaches, the accuracy of modelling results is heavily dependent on the accuracy of boundary conditions. Where there is uncertainty about the accuracy of boundary conditions, the variability of the inputs in the Monte Carlo analysis should be increased to reflect this.
- The attributes and risk factors used for the risk ranking process should be relevant to the local context.
- Following sampling on a subset of ponds, the inputs and outputs of the modelling process should be evaluated against real data to provide a validation of the approach. Inputs should be modified and models re-run if necessary to improve the accuracy of the process. A preliminary comparison of the models and field data, although based on very limited data, indicates very good agreement.
- Where significantly different types of pond systems have been assessed using this process, it would be prudent to include an example of each type of system in the physical sampling and validation process if resources and circumstances permit.

REFERENCES